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EXPERIMENTAL AND CFD ANALYSIS OF HEAT TRANSFER IN A DOUBLE PIPE HELICAL COIL HEAT EXCHANGER

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ABSTRACT

This study examines the heat transfer process in counter flow of double pipe heat exchanger, experimentally and numerically. The material used for inner tube construction is copper and Polypropylene Random (PPR) for the outer tube (shell). Numerical study was performed with the aid of Solid Works. Water is considered to be the fluid, passing through outer casing and the inner tube. The results reported an efficient cooling to the inner tube, by using helical coil PPR material technique. The heat exchanger under study has been subjected to different cases, including changing the mass flow rate of inner tube and raising shell temperature with constant flow rate for shell and tube. Increasing the shell temperature by 10%, records higher effectiveness of 53%, because of higher number of heat transfer units that are is based on rate of heat capacity for hotter fluid (tube). The numerical simulation using Solid works finds a nice reduction in the hot surface temperature from 351 K to 333 K, due to the occurrence of pressure drop in the helical tubes. The experimental results are compared with the numerical simulation, and 2% error is reported.

KEYWORDS: Helical Coil, Double Pipe Heat Exchanger & Effectiveness

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Original Article

1. INTRODUCTION

The usage of helical tubes is observed in different applications such as processing of foods, the operation of nuclear reactor, heat recovery system, and medical equipment [1]. The Helical coil offers a massive area of heat transfer with a small spaces, as well as higher coefficient of heat transfer together with less distribution of residence time. Another positive point of utilizing helical coil, instead of straight tube is the reduction in the residence time, which reduces the axial dispersion in the reactor [2]. Thus, in order to design helical coiled heat exchanger, the characteristics of heat transfer should be investigated. Some of the research papers available in the open literature are summarized in the next lines. The pressure drop and friction factor has been investigated in an inclined helical coil with two phase flow by **Guo et al. [3]**. The results reported major dependence pressure drop increase on angle of inclination .**Mrunal et al. [4],** designed a compact double pipe helical coil, in such a way to offer more fluid contact and eliminate the dead zones. Obviously, an increase in the turbulent heat transfer rate has been noticed. Different correlation between flow rate and pressure drop for helical coil has been developed by **Ali [5]**. The research covers laminar zones up to turbulent zones. Reynolds number, as well as new number depends on coil diameter, and length of coil tubes studied. The simulation of turbulent flow in helical coil has been investigated by **Friedrich and Hüttl [6],** in order to study the torsion and curvature effects. The secondary flow is increased, because of torsion effects, as well as clear reduction in the turbulent kinetic energy is observed due to curvature. It is found that, the torsion increases the secondary flow effect and tended to change its pattern, while having negligible effects on the axial velocity .**Timothy J. Rennie [7]** studied the characteristics of heat transfer in

a double pipe helical heat exchanger. A constant wall temperature and heat flux is studied. The results found that, the inner dean number varied directly with overall heat transfer coefficient; however the conditions of fluid flow in the outer pipe had a major contribution on the overall heat transfer coefficient. The laminar flow situations in helical coil heat exchanger are carried out by **Rennie and Raghavan [8-9]**. The exchange of heat transfer between cold and hot fluids, as well as pressure drops has been simulated using Phoenics V 3.3. The overall coefficients of heat transfer for both parallel and counter flows are studied.

MandhapatiRaju et al [10] studied a 3-D COMSOL model, to simulate the heat transfer and exothermic chemical reactions in a helical coil heat exchanger. Few number of coil turns are considered in this model, because of memory limitations. The temperature distribution for a case study is presented. A parametric study is conducted using COMSOL-Matlab interface to obtain the optimum, helical pitch and radius. **Pramod et al [11]** investigates a comparative analysis of the different correlations given by the different researchers for helical coil heat exchanger. The results indicate that, helical coils are efficient in low Reynolds number. The analysis reported an increase in the diameter of tube, with constant coil diameter. The ratio of curvature is increased .**Sidda R. et al [12]** focused on the increasing of the effectiveness through analyzing different parameters which affects the effectiveness of heat exchanger. The coils number, temperatures and flow rate are considered as well. The results are compared with the results of straight pipes heat exchanger for parallel and counter flow. **Nandan G. at al [13]** examined the performance of heat transfer and the analysis of energy in shell and tube heat exchanger by injection air bubbles at various points in the tube. This technique is adopted, in order to increase the turbulence, and hence the heat transfer characteristic is improved. **Al-Dawody et al [14]** studied theoretically the effect of curved pipe heat exchanger, and compares it with the straight heat exchange pipe. Both pipes are subjected to different boundary conditions, according to inlet shell temperature and inlet tube mass flow rate. The effectiveness of the curved pipe is higher than straight pipe, as longer time to exchange heat between hot and cold fluids is observed, because of the curvature of the pipe. The maximum effectiveness reached is 13.75% at 363 K for curved heat exchanger with 0.22 kg/s inlet tube mass flow rate and fixed inlet shell temperature, while it was 12.15% at 363 K for the straight pipe heat exchanger. **Thakur G. et al [15]** investigated the effect of injection air bubbles at different locations in the entrance of shell and tube heat exchanger for different percentages of Al_2O_3nano particles. An enhancement in the characteristics of heat transfer is observed at the tube inlet. 25% improvement in the coefficient of heat transfer is recorded with 0.2 % of nano particles.

The main goal of this paper is to determine the optimum operating conditions for the present design, and the characteristic of heat transfer in a double-pipe helical heat exchanger with various inner tube temperature flow rate (laminar region). Counter flow is considered in the present model. The Solid Works is used to predict the temperature contours as well as flow profiles in the proposed helical heat exchanger.

2. EXPERIMENTAL SETUP

In this work, number of designing factors has been considered.

- Minimized heat transfer resistance.
- Lower cost as well as requirement of materials.
- Avoidance of corrosion

- Lower cost for pumping.
- The required weight and space must be minimized.

This section starts with curving the copper pipe and inserting it in the PPR pipes as shown in the figure (1), where, bending and curving of pipes around a fixed base is by using bending instrument. The diameters of copper pipe are chosen 0.5 inches, while the PPR diameter is chosen 1 inch. The insertion of copper pipe is done in such a way, to reduce the dead zones as much as possible.

The pitch diameter of helical coil is (2.3 inch) with 6 turns. The test rig consists of tank to supply cold water, heater to supply hot water, two motors, for pumping the flow of hot and cold water, two ventures to measure the flow rate of water and four thermo couples for reading the input and output temperatures of hot and cold water through the helical coils. All the electrical cables and thermocouples are connected to a master mother board to switch in/off device. The counter flow is considered in this work. The complete heat exchanger test rig is shown in figure (2)

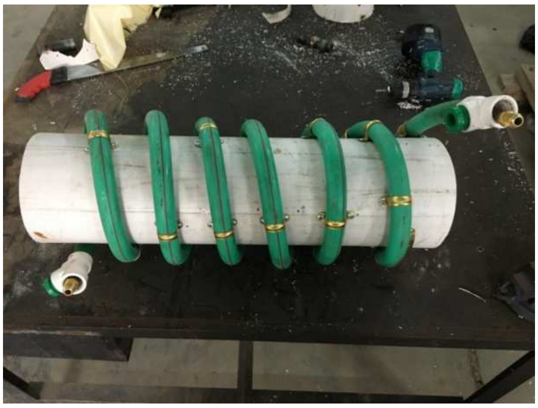

Figure 1: Bending the Helical Coils around Fixed Base

Figure 2: Helical Coil Heat Exchanger test Rig

3. SIMULATION MODEL

In this work, some reasonable assumptions are considered as given below:

- Steady and single phase-flow.
- Conjugated heat transfer between inner and outer pipes is considered.
- The change in the potential and kinetic energy are negligible.

- Constant specific heat.
- Adiabatic outer wall conditions**.**
- Negligible heat conduction in the axial direction is considered.

The conservation equations of mass, angular momentum and energy govern the flow of the fluid in helical tubes of the heat exchanger can be written as follows [14]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial p}{\partial x_i} = \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{ij}^R) + S_i i = 1,2,3 \tag{2}$$

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial}{\partial xi}\left(u_j(\tau_{ij} + \tau_{ij}^R) + q_i \quad\right) + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H \tag{3}$$

$$H = h + \frac{u^2}{2} \tag{4}$$

$$\varepsilon = \frac{T_{\max in} - T_{\max out}}{T_{\max in} - T_{min}} \tag{5}$$

4. NUMERICAL ANALYSIS

The CFD Analysis applies various numerical schemes, in addition to algorithms to solve and analyze problems, which include fluid flow. The surface of interaction with fluid, has to be simulated by applying the initial and boundary conditions, which are done using Solid Works [16]

4.1. Geometry

The geometry of helical coil is created in the Solid works workbench design module. Figure 3 and 4 display the geometry of the double pipe, as well as a close up region to the concentric tubes.

Figure 3: Solid Work Model

Figure 4: Close-up of Double-Pipe Heat Exchanger

4.2. Mesh Generation

The mesh in the simulation of flow has a rectangular section, anywhere in the domain. The sides of mesh cells have met the system of Cartesian coordinate, orthogonally. Nevertheless, because of special measures, the heat flux as well as mass is treated in a proper way in such cells, and called partial. The 3D view of mesh is shown in figure 5. The detailed computational mesh for helical coils comes with 2141 fluid cells and 10256 solid cells, in addition to 19824 partial cells.

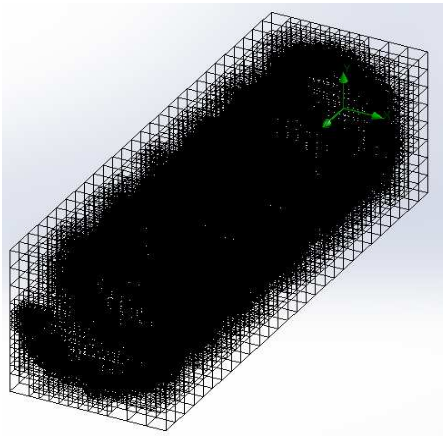

Figure 5: 3D Mesh Generation of Double-Pipe Heat Exchanger

4.3. Boundary Conditions

The boundary condition depends on the requirements of model. The consideration of the boundary conditions for this model is shown in figure 6. Table (1) presents the boundary conditions used in this paper

Table 1: Boundary Conditions

Boundary Condition Case1	Curved Pipe Copper (Tube)	Curved Pipe PPR (Shell)
Inlet mass flow rate	0.2 kg/s	0.8 kg/s
Inlet temperature	343-361 K	283 K
Inlet Pressure	101325 Pa	101325 Pa
Exit Pressure	101325 Pa	101325 Pa
Boundary Condition Case2	**Curved Pipe Copper (Tube)**	**Curved Pipe PPR (Shell)**
Inlet mass flow rate	0.22 kg/s	0.8 kg/s
Inlet temperature	343-375 K	283 K
Inlet Pressure	101325 Pa	101325 Pa
Exit Pressure	101325 Pa	101325 Pa

Table 1: Contd		
Boundary Condition Case3	**Curved Pipe Copper (Tube)**	**Curved Pipe PPR (Shell)**
Inlet mass flow rate	0.2 kg/s	0.8 kg/s
Inlet temperature	343-361 K	293 K
Inlet Pressure	101325 Pa	101325 Pa
Exit Pressure	101325 Pa	101325 Pa

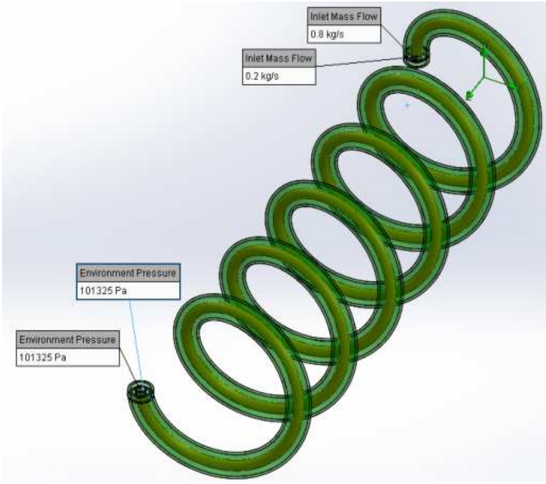

Figure 6: Consideration of Model Boundary Conditions

5. RESULTS AND DISCUSSIONS

The number and the shape of turns in the helical heat exchanger plays crucial role in the performance of the present work, since the drag and swirl increasing the turbulent flow for enhances the heat transfer. Figure (7) shows the distribution of hot water temperature surface plot. The hot water flow starts with initial inlet temperature of 351 K, then with increasing in the distance the flow temperature will be decrease to be 333 K. This is due to the high pressure drop and shell cooling in the helical tubes. Figure (8), an opposite observation is recorded in the cold water temperature surface plot. The shell water flow starts with 310 K and leaves the helical coils with 320 K. The shell tube cools down the inner tube, efficiently. It can be seen from figure (9) that conjugate heat transfer, which is happening through a solid surface, the gradient in the temperature from the center of the inlet hot flow and the outer cold flow at all sections. Also, the first section of the hot flow differs from the last section of the inlet cold flow due to the enhancement of heat transfer.

All the results of temperature gradient contours are supported by Figure (10) for the center line tube helical heat exchanger. From the above, the number of the turns depends on the required temperature range that the design needed. For more accurate results, the study achieved an experimental work to determine the effectiveness, and then compared it with simulation works for different cases.

Case 1 Figure (11) for, the experimental and simulation results have the same behavior. The effectiveness increases as the inlet tube temperature increases up to 360 K with same values of the effectiveness 0.48. The reduction in the effectiveness occurs at 364 K, as the higher inlet and outlet tube temperatures affect on the efficiency of heat exchanger. Also, lower flow rate, in case 1 leads to lower Reynolds number and then Nusselt number, vise versa. 2% is the percentage of error reported between experimental and simulation analysis.

Case 2_Figure (12) shows the second case in which, the tube mass flow rate increases 10%, leading to continuous increase in the effectiveness of helical heat exchanger, but with less values of effectiveness reaches to 0.47 at less inlet temperature. The same value of the effectiveness is recorded for case 1 and 2 at 365 K, so the working range for case 2 is higher than case 1.

Case 3 Figure (13) shows higher values of the effectiveness (0.53) due to higher inlet shell temperature 293 K, while in case 1 and 2, the inlet shells temperature was 283 K, but at the same mass flow rate for tube and shell. It is seen that for case 3, the efficiency for the helical heat exchanger are continuously increasing until 375 K for inlet tube temperature. Case 3 refers to an important point, that we can use the water environment temperature without any effort to cool down the hotter fluid as compared to other cases.

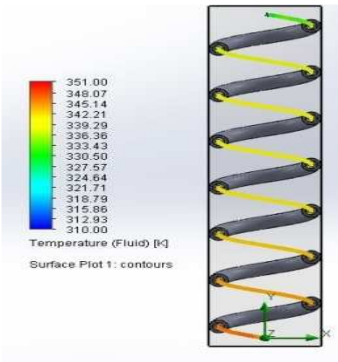

Figure 7: Hot Water Temperature Surface Plot

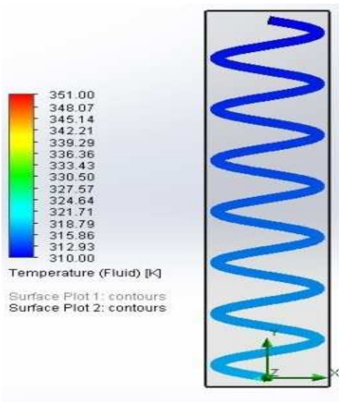

Figure 8: Cold Water Temperature Surface Plot

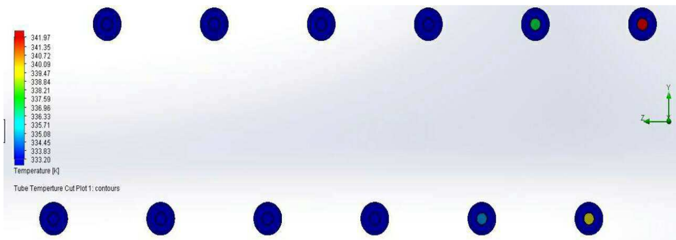

Figure 9: Inner Tube Couture Temperature

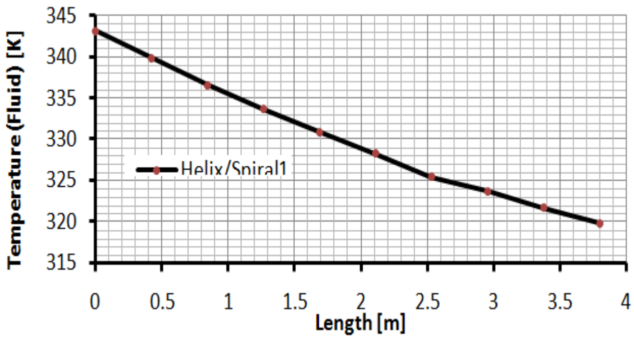

Figure 10: Temperature Development along Tube Heat Exchanger

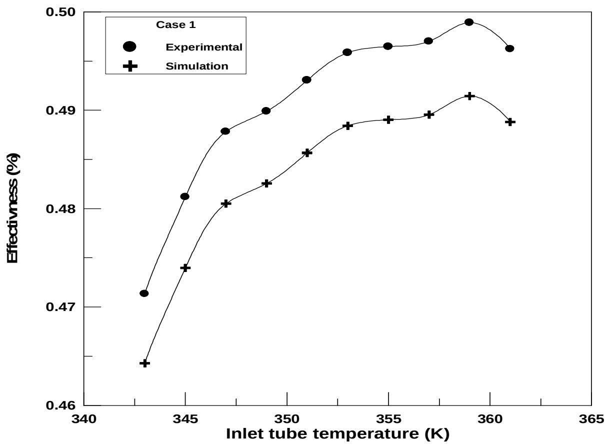

Figure 11: Case (1) Effectiveness vs. Inlet Tube Temperature for Experimental and Simulation Results

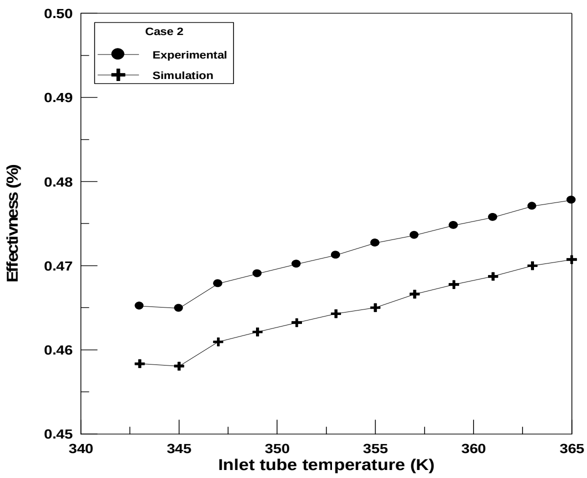

Figure 12: Case (2) Effectiveness vs. Inlet Tube Temperature for Experimental and Simulation Results

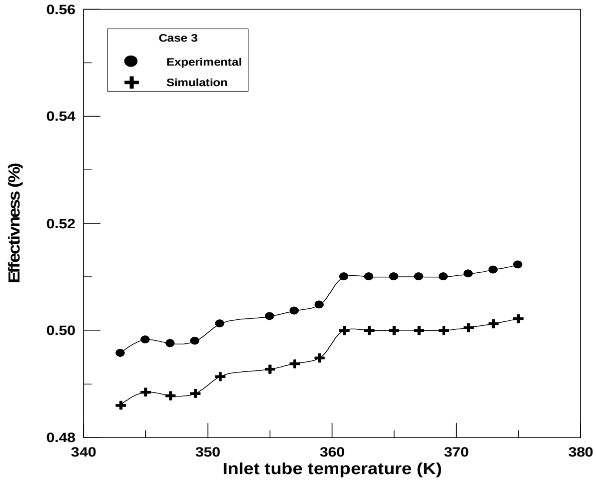

Figure 13: Case (3) Effectiveness vs. Inlet Tube Temperature for Experimental and Simulation Results

6. CONCLUSIONS

- The fluid has more time to be in contact (to exchange heat), because of larger surface area as a results of using helical pipes rather that straight pipes.
- The experimental results are compared with CFD results and 2% difference is recorded.
- Polypropylene Random (PPR) is a promising material as a shell tube, which can be used to cool down the inner tube, efficiently.
- Case 3 is the best case, which gives best performance for the heat exchanger (optimum operating conditions).

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